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Evaluation of Impulse Noise Criteria Using Human Volunteer Data

Jaycor Technical Report J299729-99-104

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EXECUTIVE SUMMARY

The evaluation of impulse noise criteria is becoming more critical as many new weapons exceed exposure levels for single hearing protection set forth by the MIL-STD-1474D. Previous man-rating studies have consistently shown that auditory injury does not occur at these levels. Consequently, there is general belief that the current standards underpredict the threshold at which injury occurs. Four impulse noise auditory injury criteria adopted by NATO countries, namely, the MIL-STD-1474D (USA), Pfander (Germany), Smoorenburg (Netherlands), and L_{Aeq8} (France), are evaluated against human volunteer data. Four data sets from subjects wearing single hearing protection exposed to increasing blast overpressure effects were obtained from tests sponsored by the US Army Medical Research and Materiel Command. Two data sets were obtained from free field and bunker tests using RACAL earmuffs modified to simulate poor fitting. Two other data sets came from the M198 howitzer and Viper man-rating studies using EAR earplugs. Injury threshold was taken as a temporary threshold shift (TTS) $\geq$ 25 dB at any frequency. Using logistic regression, the four criteria were each correlated with the test data. The analysis shows that all four criteria are overly conservative by 4-12 dB. The MIL-STD-1474D for single hearing protection is 9.9 dB lower than the 95% protection at 95% confidence band for this particular group of subjects. Similarly, the thresholds for 95% protection at 95% confidence for Pfander, Smoorenburg and L_{Aeq8} are 195.9, 203.2 and 114.7 dB, respectively with single hearing protection. These results can help guide a revision of the criteria for impulse auditory injury.

Nomenclature

$\hat{C}$	Hosmer-Lemeshow goodness-of-fit statistic for logistic regression
g	Logit function
$g_{\pm}$	Confidence interval in logit space
L	Effective exposure level
L_{Aeq8}	Eight hour equivalent A-weighted sound exposure level
L_M	Effective exposure level for Mil-Std-1474D
L_P	Effective exposure level for Pfander criterion
L_{pk}	Peak sound pressure level (dB)
L_S	Effective exposure level for Smoorenburg criterion
m_o	Observed number of failures in a test group
m_p	Presumed failures
n	Sample size of a test group
n_k	Number of data points in a data group
o_k	Observed failures in a data group
P_{max}	Peak pressure of the free field incident wave
P_{ref}	Reference value of 20 μPa
SEL_P	P-weighted energy
SEL_{P1}	P1-weighted energy
SEL_{P2}	P2-weighted energy
SEL_R	R-weighted energy
$SELA_8$	A-weighted 8-hr equivalent sound exposure level for one pulse
T_B	B-duration
T_C	C-duration
T_D	D-duration

β	Parameter coefficients for the logistic fit
$\Phi(z_x)$	Accumulative standardized normal distribution function
$\sigma_o, \sigma_1, \sigma_{01}$	Standard deviations
π	Probability of failure
$\overline{\pi_k}$	Average predicted failure rate in k-th data group

1. INTRODUCTION

Evaluation of impulse noise criteria is becoming more critical as new weapons tend to exceed exposure levels for single hearing protection set forth by auditory damage risk criteria (DRC), such as the MIL-STD-1474D [Military Standard, 1991] in the USA. Standards for field application must still use free field pressure data because there is still no validated standard method to account for hearing protectors by relating pressures at the ear canal to injuries. Nevertheless, there is general belief that the current standards are overly conservative. Previous effort to evaluate the current standards using human data with adequate statistics has been limited.

The objective of this paper is to evaluate four major impulse noise auditory injury criteria used by NATO countries against data obtained from human volunteers wearing single hearing protection. The four criteria evaluated are the MIL-STD-1474D (USA), Pfander [Pfander et al., 1980] (Germany), Smoorenburg [Smoorenburg, 1992] (Netherlands), and L_{Aeq8} [Dancer, 1995] (France). Four data sets from human walk up study tests sponsored by the US Army Medical Research and Materiel Command (USAMRMC) [Johnson, 1994 and 1997; Patterson et al., 1985; and Patterson et al., 1987] were used. The data cover free field tests with ear muffs, bunker tests with ear muffs, the Viper tests with earplugs, and the M198 tests with earplugs. The results will be used to recommend an interim impulse noise DRC to USAMRMC for auditory hazard assessment.

2. METHOD

2.1 Criteria Definition

Each injury criterion defines its effective exposure level that is to be kept within a limit, as shown in Table 1. Normalized to dB, each effective exposure level is calculated from waveform parameters, such as the peak pressure and some form of duration. Figure 1 shows the definition of the four waveform durations commonly used to characterize blast overpressures, namely, the A-duration T_A, the B-duration T_B, the C-duration T_C, and the D-duration T_D. While T_A only captures the primary positive phase, T_C, T_B and T_D provide some measures for complex waveforms. If the same shot is repeated N times, some form of trading rule is used. All durations are expressed in milliseconds (ms) in this report.

Table 1. Criteria Definition.

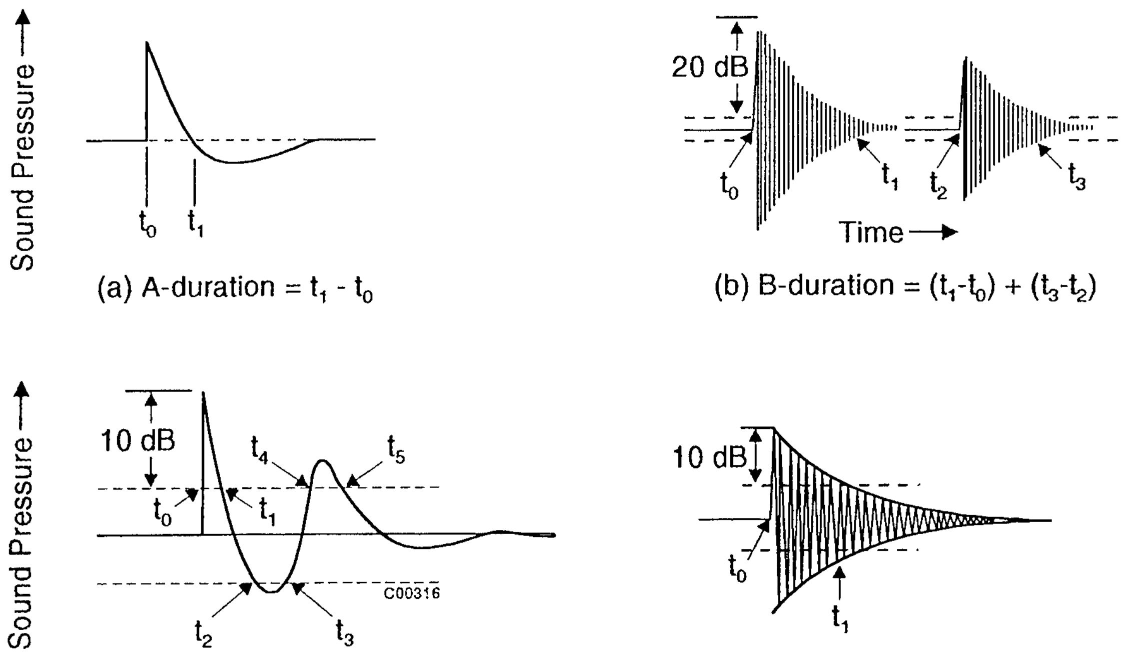
Criteria	Effective Exposure Level (dB)	Limit (dB)
MIL-STD-1474D (1991)	$L_M = L_{pk} + 6.64 \log (T_B/200) + 5 \log N$	$L_M \leq 177$
Pfander (1980)	$L_P = L_{pk} + 10 \log T_C + 10 \log N$	$L_P \leq 189.6$
Smoorenburg (1980)	$L_S = L_{pk} + 10 \log T_D + 10 \log N$	$L_S \leq 191.2$
FCWN L_{Aeq8} (1995)	$L_{Aeq8} = SELA_8 + 10 \log N$	$L_{Aeq8} \leq 110$

The MIL-STD-1474D calculates its effective exposure level L_M using the peak sound pressure level (SPL) L_{pk} and T_B normalized by 200 ms, with a 5 log N trading rule (Table 1). The peak sound pressure level, L_{pk}, is

$$L_{pk} = 10 \log (P_{max} / P_{ref})^2 \qquad (1)$$

where P_{max} is the peak pressure of the free field incident wave, and P_{ref} is the reference value of 20 μPa. For single hearing protection, the limit for MIL-STD-1474D is $L_M \leq 177$ dB (Table 1).

Similarly, Pfander calculates the effective exposure level L_P using L_{pk} and T_C normalized by 1 ms with a 10 log N trading. Smoorenburg uses L_{pk} and T_D with a 10 log N trading. For single hearing protection, 25 dB is added to raise the limits for Pfander and Smoorenburg to $L_P \leq 189.6$ and $L_S \leq 191.2$ dB, respectively (Table 1).



(a) A-duration = $t_1 - t_0$ (b) B-duration = $(t_1-t_0) + (t_3-t_2)$

(c) C-duration = $(t_1-t_0) + (t_3-t_2) + (t_5-t_4)$ (d) D-duration = $t_1 - t_0$

Figure 1. Definition of impulse noise duration.

Proposed by the French Committee for Weapon Noises (FCWN), the effective exposure level L_{Aeq8} is the 8-hr equivalent A-weighted energy with a 10 log N trading rule, where $SELA_8$ is the 8-hr equivalent A-weighted sound exposure level (energy) of a single shot (Table 1). Sound exposure level is the integral of pressure squared over the entire pulse. To account for single hearing protection, 25 dB is added to raise the limit to $L_{Aeq8} \leq 110$ dB, following the procedure of Dancer [Dancer, 1995] for using free field data (Table 1).

2.2 Human Volunteer Data

Four human volunteer data sets were used for the present work. Two data sets were obtained from volunteers wearing modified ear muffs in free field and bunker conditions [Johnson, 1994 and 1997], and the other two data sets were obtained from man rating studies using earplugs for the M198, 155mm howitzer [Patterson et al., 1985] and the Viper antitank weapon [Patterson et al., 1987], respectively. The selected data sets and the tests are described briefly as follows, where the details of the experiments can be found in the cited references.

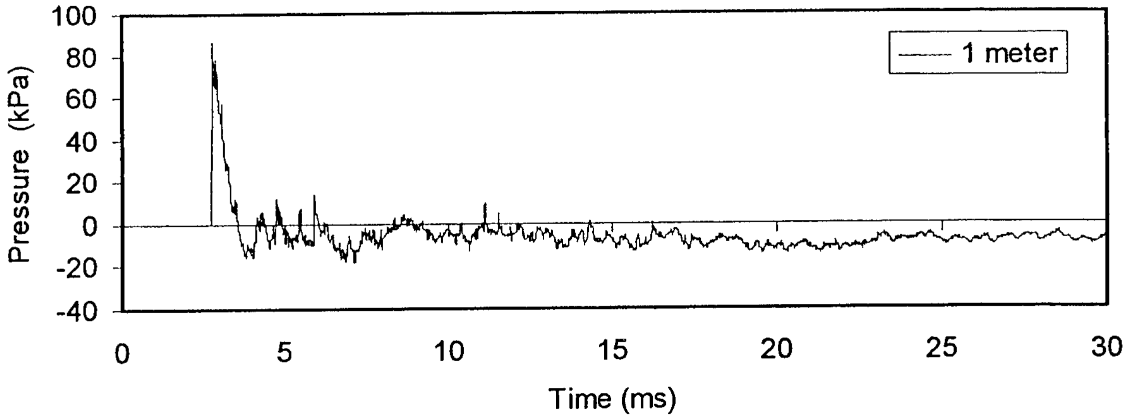
2.2.1 BOP Free Field (Mortar) Tests

To obtain systematic data for criteria evaluation, the US Army Medical Research and Materiel Command sponsored a test program from 1990-1997 at the Albuquerque blast overpressure (BOP) site [Johnson, 1984] with human volunteers wearing single hearing protection. For free field data, we selected the series of tests with subjects wearing the US Army RACAL muffs modified by inserting plastic tubes into the seals to introduce leaks to simulate poor fitting. Compared to the unmodified muffs, the real ear attenuation threshold (REAT) for the modified muff was reduced by about 10 dB across all frequency [Johnson, 1994]. Containing a large portion of the data for the present analysis, the free field tests are also labeled as mortar tests.

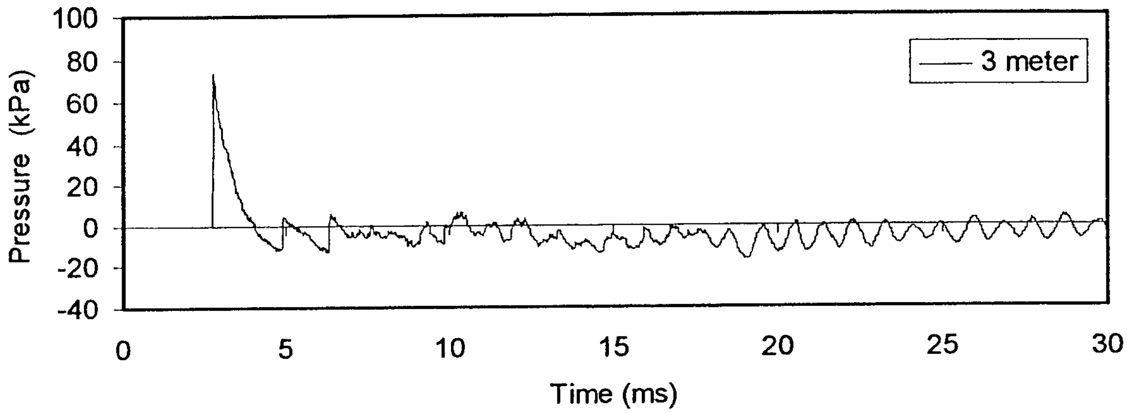
The free-field tests were conducted at three distances, 1 m, 3 m, and 5 m, each with seven intensity levels, with the L_{pk} increasing by about 3 dB per level, corresponding to doubling of P_{max} (Eq. 1). The typical waveforms at the three distances resulted in A-durations of about 0.8, 1.5 and 2.8 ms, respectively (Figure 2). The range of L_{pk} is 174-196 dB. Using the MIL-STD-1474D, doubling N results in 1.5 dB increase in the effective exposure level L_M (Table 1). The exposure levels were all above the unprotected auditory threshold of L_{pk} = 140 dB but below the nonauditory limit. The right ear was the test ear facing normal to the charge, and the left ear was always wearing double protection.

For each distance, the subjects were exposed in a walk-up procedure with stepwise increase in the effective exposure level. Three separate groups of subjects were selected for the three distances, respectively, each with an initial group size n ranging from 59-68. Table 2 presents the test matrices and the derived data used for the present analysis. As shown, each box in a matrix refers to a test for a specified distance, peak sound pressure level and number of shots (Table 2). For each distance, starting with six shots (N = 6), the subjects were first exposed to increasing L_{pk} levels, from 1-7, followed by stepwise increase of N to 100 shots at level 6 (Table 2). Tests were also conducted for level 5 at 100 shots at 1 m and 3 m (Table 2a, b). A subject was tested no more than once a day. A small number of subjects dropped out at higher levels and N due to auditory failures or subjects' choice (Table 2). A total of 192 male subjects participated, with over 2000 subject-test exposures. Each subject carried a pass/fail condition for each test condition.

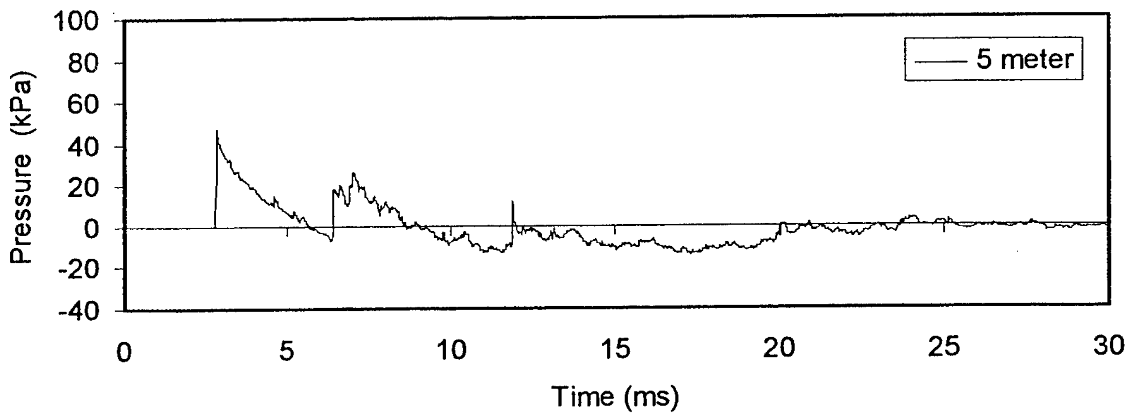
Failure threshold was taken as a temporary threshold shift (TTS) ≥ 25 dB at any frequency, which was measured 2 min after the test. A conditional failure was defined as TTS ≥ 15 dB but was not a failure. However, when a subject experienced a failure or a conditional failure at a certain L_{pk} level and N shots, he would be presumed to fail at all higher L_{pk} levels and higher N exposures without actually being exposed (Table 2). Likewise,



(a) 1-m test



(b) 3-m test



(c) 5-m test

Figure 2. Typical waveforms from mortar tests (Level 7).

Table 2. Free Field Walk-up Test Matrix and Results.

(a) 1-Meter Distance

L_{pk} Level	Number of Exposures (N): 6	12	25	50	100
7	L_M = 194.1 2 58 6.90% 2				
6	L_M = 191.6 0 62 3.23% 2	L_M = 193.1 2 61 9.84% 4	L_M = 194.3 2 61 13.11% 6	L_M = 195.9 0 54 18.52% 10	L_M = 198.7 1 41 39.02% 15
5	L_M = 186.0 1 62 3.23% 1				L_M = 191.5 4 24 45.83% 7
4	L_M = 181.9 0 63 1.59% 1				
3	L_M = 179.4 0 63 1.59% 1				
2	L_M = 176.6 0 64 0.00% 0				
1	L_M = 173.8 0 65 0.00% 0				

Key:

L_M	m_o
n	
π	m_p

- L_M: Mil-Std-1474D Effective Level
- m_o: Number of Failures Observed
- n: Number of subjects in a test group
- π: Failure Rate
- m_p: Number of Failures Presumed

Table 2. Free Field Walk-up Test Matrix and Results.

(b) 3-Meter Distance

Number of Exposures (N)

L_{pk} Level	6	12	25	50	100
7	L_M = 192.7 0 47 10.64% 5				
6	L_M = 188.8 2 64 7.81% 3	L_M = 190.4 1 64 9.38% 5	L_M = 191.7 2 62 12.90% 6	L_M = 193.2 2 58 17.24% 8	L_M = 194.6 2 37 32.43% 10
5	L_M = 185.4 1 66 3.03% 1				L_M = 191.3 0 23 17.39% 4
4	L_M = 182.4 0 68 0.00% 0				
3	L_M = 179.1 0 68 0.00% 0		L_M m_o n π m_p		
2	L_M = 176.4 0 68 0.00% 0				
1	L_M = 173.7 0 68 0.00% 0				

Mil-Std-1474D Effective Level (L_M)

Number of Failures Observed (m_o)

Number of subjects in a test group (n)

Failure Rate (π)

Number of Failures Presumed (m_p)

Table 2. Free Field Walk-up Test Matrix and Results.

(c) 5-Meter Distance

Number of Exposures (N)

L_{pk} Level	6	12	25	50	100
7	L_M = 189.1 0 55 1.82% 1				
6	L_M = 185.9 0 57 0.00% 0	L_M = 187.2 0 57 1.75% 1	L_M = 189.2 0 57 1.75% 1	L_M = 190.3 0 57 1.75% 1	L_M = 191.9 1 56 5.36% 2
5	L_M = 183.2 0 57 0.00% 0				
4	L_M = 180.5 0 58 0.00% 0				
3	L_M = 178.0 0 59 0.00% 0				
2	L_M = 175.4 0 59 0.00% 0				
1	L_M = 172.3 0 59 0.00% 0				

Mil-Std-1474D Effective Level → L_M	Number of Failures Observed → m_o
n ← Number of subjects in a test group	
Failure Rate → π	Number of Failures Presumed → m_p

according to the original test design, a pass at a certain test condition presumed passes at all lower L_{pk} levels and N. Subjects with failures or conditional failures were allowed only to be exposed at lower L_{pk} levels with higher N after recovery. For the present work, presumed failures were included for regression analysis, but presumed passes were excluded. This approach is considered conservative. Therefore, for each test in the test matrix (Table 2), the total number of failures is the sum of observed and presumed failures (m_o+m_p). The total number of subjects in each test, n, is the sum of subjects actually tested plus presumed failures (Table 2). Hence, the failure rate π for each test is (m_o+ m_p)/n.

As shown in Tables 2a-c, we only consider the data from the test boxes where the group of subjects walked up together for each distance. A subset of tests were conducted at the empty boxes below level 6 with N > 6 for a small number of selected subjects with prior failures or conditional failures (See Appendix). Since these tests were biased, the data were not included in our analysis (Table 2). The outcomes of these tests primarily confirm the presumed failures for these subjects at level 6 and 5 for N > 6 as shown in Table 2. The pass/fail data for all subjects are shown in Figures A-3 through A-11 in the Appendix.

To prepare the data for analysis, we carried out an extensive effort to verify and scrub the data obtained from the BOP test program. We cross-checked the walk-up test data and established a database containing the auditory results for all subjects throughout the tests. The waveform parameters (L_{pk}, T_B, L_{Aeq8}, etc.) were calculated from statistical averages of all the available data traces, which required us to practically analyze every trace and recalculate all parameters. Details of the data scrubbing effort are described in the Appendix, covering both the mortar and bunker data used for the present work.

2.2.2 BOP Bunker Tests

The second data set was also from the BOP human volunteer tests using the modified muff performed inside a bunker to study the effects of complex waves [Johnson, 1997]. As shown in the test matrix in Table 3, the test was designed to have seven intensity levels similar to the Free Field Tests. Beginning with one shot, the subjects were first exposed with increasing L_{pk} up to level 7 (Table 3). At level 6, N was then increased to 2 and 3. Failure was defined in the same way as the Free Field Tests above. However, the Bunker tests resulted in no auditory failures (Table 3). Details of the data scrubbing effort are described in the Appendix, with the subject pass/fail data shown in Figures A-12 and A-13.

Table 3. Bunker Walk-up Test Matrix and Results.

Number of Exposures (N)

L_{pk} Level	1	2	3	
7	L_M = 182.5 0 59 0.00% 0			
6	L_M = 181.5 0 59 0.00% 0	L_M = 183.0 0 59 0.00% 0	L_M = 183.9 0 59 0.00% 0	
5	L_M = 176.6 0 61 0.00% 0			
4	L_M = 172.4 0 61 0.00% 0	Mil-Std-1474D Effective	Number of Failures Observed	
3	L_M = 169.4 0 63 0.00% 0	Level	L_M m_o n ← π m_p	Number of subjects in a test group
2	L_M = 167.3 0 63 0.00% 0	Failure Rate	Number of Failures Presumed	
1	L_M = 165.7 0 64 0.00% 0			

2.2.3 M198 Tests

The third data set was obtained from the man rating tests for the M198, 155mm howitzer using three propelling charges [Patterson et al., 1985]. Since the weapon produced peak SPL as high as 182 dB in crew areas that exceeded published DRCs, man rating studies were carried out to evaluate the adequacy of hearing protection for crew members. The tests were conducted by the US Army Aeromedical Research Laboratory (USAARL) and Walter Reed Army Institute of Research (WRAIR) [Patterson et al., 1985]. Fifty-nine volunteers wearing the E-A-R earplugs were exposed to the M198 noise in a progression manner up to 12 shots. No auditory failures were observed. Table 4 shows the test matrix. The test data and averaged waveform parameters are obtained from the test report [Patterson et al., 1985].

Table 4. Summary of M198, 155mm Towed Howitzer Study.

Charge	Peak Pressure (dB)	Number of Exposures	Number of Subjects	Number of Injuries
M4A2	173.3	12	59	0
M119A2	177.7	12	59	0
M203	180.8	12	59	0

2.2.4 Viper Tests

The fourth data set was obtained from the man rating tests for the Viper antitank weapon which also produced peak SPL as high as 182 dB, exceeding that allowed by MIL-STD-1474. The tests were conducted by USAARL [Patterson et al., 1987]. Wearing the E-A-R earplugs, thirty-eight volunteers participated in the tests with exposure up to two rapid shots. Table 5 presents the test matrix. No auditory failure was observed. The Viper data report contains only information for evaluation of the MIL-STD, because T_C, T_D and A-weighted energies are not shown in the report.

Table 5. Summary of Viper Study.

Location	Peak Pressure (dB)	Number of Exposures	Number of Subjects	Number of Injuries
Left side and 10 dB below Gunner	171.2	1	8	0
Left side and 5 dB below Gunner	176.8	1	8	0
Gunner	181.3	2	38	0

2.3 Statistical Analysis

The data were analyzed by logistic regression [Hosmer et al., 1989]. Based on our consultation with Prof. David Hosmer in the School of Public Health at the University of Massachusetts, he recommended us to use the population-averaged model with exchangeable autocorrelation [Zeger et al., 1986, Hosmer, 1999]. The data were treated as longitudinal since the subjects "walked" through a test series from low to high exposure levels with repeated testing. Hence the subject responses are not independent between tests. The autocorrelation relationship of a subject's outcomes between different exposure levels was modeled as a constant exchangeable coefficient in the correlation matrix. The statistical computation was carried out using the STATA software [STATA, 1999].

We define the logit g as a function of the probability of failure, π,

$$g = \ln[\pi /(1- \pi)] \tag{2}$$

and we model g as a linear function in the logit space

$$g = \beta_0 + \beta_1 L \tag{3}$$

where L is the effective exposure level for each criterion (T_M and T_P etc. in Table 1), and β_0 and β_1 are the model coefficients. The covariate variable L is assumed to be continuous. For the regression analysis, the values of L were calculated from the measured waveform parameters. From the regression calculations using the data, we will only obtain the estimated values $\hat{\beta}_0$ and $\hat{\beta}_1$ for the coefficients β_o and β_1 in Eq. 3. If g is known, π is calculated as

$$\pi = \frac{e^g}{1+e^g} \tag{4}$$

The regressions can be assessed by calculating the Hosmer-Lemeshow goodness-of-fit statistics $\hat{C}$. To accomplish this, the data are divided into 10 groups each with approximately equal number of subjects sorted by increasing predicted failure rate. The Hosmer-Lemeshow statistic $\hat{C}$ is

$$\hat{C} = \sum_{k=1}^{10} \frac{\left(o_k - n_k \bar{\pi}_k\right)^2}{n_k \bar{\pi}_k \left(1 - \bar{\pi}_k\right)} \tag{5}$$

where o_k is the observed failures in each group, n_k is the number of data points in the k^{th} group, and the corresponding average predicted failure rate is

$$\overline{\pi_k} = \frac{1}{n_k} \sum_{j=1}^{n_k} \hat{\pi}_j \tag{6}$$

and $\hat{\pi}_j$ is obtained from the fitted logit value $\hat{g}_j = \hat{\beta}_0 + \hat{\beta}_1 L_j$ (Eq. 4). The goodness-of-fit can be judged by the p-value, $P[\chi^2 \geq \hat{C}]$, according to the Chi-square distribution with 8 degrees of freedom.

The confidence interval (CI) for the fitted model was calculated based on the assumption of normal distribution of the error of the regression, since we had quite a large number of data points from all the four data sets. Thus, the (1-α)100% confidence interval estimate of g can be written as a function of L as

$$\hat{g}_{\pm} = \hat{\beta}_0 + \hat{\beta}_1 L \pm z_{1-\alpha/2} \sigma \tag{7}$$

with

$$\sigma^2 = \sigma_0^2 + 2\sigma_{01} L + \sigma_1^2 L^2 \tag{8}$$

where z_x satisfies the accumulative standardized normal distribution function $\Phi(z_x) = x$.

Recommended by Prof. Hosmer [Hosmer, 1999] the standard errors σ_o, σ_1, and the covariance σ_{01} for β_o and β_1, respectively, are calculated by a robust formula according to Huber and Royall [Huber, 1967 and Royall, 1986], which relaxes the assumption of binomial error structure. The confidence interval for the probability of injury, π, is obtained by using Eq. 4,

$$\hat{\pi}_{\pm} = \frac{e^{\hat{g}\pm}}{(1 + e^{\hat{g}\pm})} \tag{9}$$

Let L[100(1-a),100(1-α)] denotes the threshold of L for 100(1-a)% of protection with 100(1-α)% of confidence. Then, L[100(1-a),100(1-α)] can be obtained by solving Equation 9 with $\hat{\pi}_+ = a$.

Our statistical method was also reviewed by Dr. Douglas Tang, Chief of Dept. of Biometrics, Walter Reed Army Institute of Research [Tang, 1999].

3. RESULTS

The logistic regression correlation results are summarized in Table 6, which compares the current criteria limits to the corresponding calculated thresholds for 95% protection with 95% confidence, L(95,95). If we begin with the free field (mortar) data set, Table 6 shows a slight increase of the L(95,95) values when additional data sets are used. Nevertheless, the results based on all four data sets (all-data) should be considered the most conclusive for evaluation of the criteria. The last column in Table 6 shows the p-values obtained from the Hosmer-Lemeshow (H-L) goodness-of-fit test for the all-data results. The best-fit model regression results are indicated in the last row. More detailed explanation for Table 6 follows.

Table 6. Logistic Regression Results.

		L(95,95) dB			
Criteria	**Current Limit (dB)**	**Mortar**	**Mortar and Bunker**	**Mortar, Bunker, M198 and Viper**	**H-L test p-value (All data)**
MIL-STD-1474D	177	185.3	186.6	186.9	0.637
Pfander	189.6	192.7	194.9	195.9	0.613
Smoorenburg	191.2	199.9	202.4	203.2	0.291
L_{Aeq8}	110	112.7	114.3	114.7	0.363
Best fit model L_{pk}-10.9log(T_B/200) + 3.42logN (All data)	N/A	200.0	200.0	200.0	0.971

Logistic regression results using all-data (mortar, bunker, M198 and Viper) indicate that the four NATO criteria are overly conservative by 4-12 dB (Table 6). The effective exposure level limit for MIL-STD-1474D can be raised from 177 to 186.9 dB for 95% protection with 95% confidence (Table 6), which is an increase of 9.9 dB. For Pfander, with all data considered, the limit can be raised by 6.3 to 195.9 dB as the L(95,95) threshold. Similarly, the Smoorenburg limit can be raised by 12 to 203.2 dB as the L(95,95) threshold. For the energy-based L_{Aeq8} criterion, the L(95,95) threshold is 114.7 dB, which is an increase of 4.7 dB from the current proposed limit (Table 6). The L(95,95) values decrease by 1-3 dB when only the free field (mortar) data are used (Table 6). Still, the mortar data indicate that the MIL-STD can be raised by 8.3 dB, and the other three criteria remain overly conservative (Table 6).

The p-values for the Hosmer-Lemeshow tests show that the mean fitted correlations using all the data are satisfactory (Table 6). In fact, the MIL-STD-1474D correlation produces the highest p-value of 0.637, with the Smoorenburg criterion showing the lowest p-value (Table 6). It should be mentioned that only the MIL-STD-1474D correlation contains the Viper data set.

For visual verification, Figures 3 to 6 present the data comparison with the all-data correlations and the 95% CI for the four NATO criteria. As shown, each plotted data symbol represents one actual test, and the legend indicates the range of the corresponding sample sizes (n). For the MIL-STD, as shown in Figure 3, the farthest data point from the correlation is the 1m mortar test at level 5 with 100 shots with n=24, resulting in the highest injury rate of 46% (see Table 2a). This data point also shows considerable deviation from the other three criteria correlations (Figs. 4 through 6). Furthermore, the 5-m mortar data are closer to the MIL-STD correlation (Fig. 3) than the Pfander, Smoorenburg and L_{Aeq8} correlations (Figs. 4 through 6). This probably explains why the MIL-STD goodness-of-fit test has the highest p-value among the four criteria (Table 6) Nevertheless, it is noted that the H-L goodness-of-fit test is highly nonlinear.

Figure 7 shows the data comparison with the best-fit model where the coefficients for T_B and N trading were obtained from the regression calculation, instead of just using those defined by MIL-STD (Table 6). That is, these coefficients were freed up to be determined by the actual logistic regression of the data. Furthermore, T_C and T_D were eliminated by the tests of statistical significance. Compared to Figures 3-6, the data are much closer to the best-fit correlation, as shown in Figure 7, with no apparent "outliers." Consequently, it is not surprising that the best-fit model also results in the best p-value (0.971) for the Hosmer-Lemeshow test (Table 6). The best-fit model results in the L(95,95) threshold of 200.0 dB, but this should not be compared with the current MIL-STD threshold of 177 dB, because the best-fit model has changed the MIL-STD definition of effective exposure level (Table 6). It should be noted that the best-fit model has a negative coefficient (-10.93) for the B-duration, which is counter to the positive coefficient specified by MIL-STD (Table 6). Furthermore, the best-fit model indicates a 3.42logN trading, instead of 5logN for MIL-STD and 10logN for the other three criteria (Table 6).

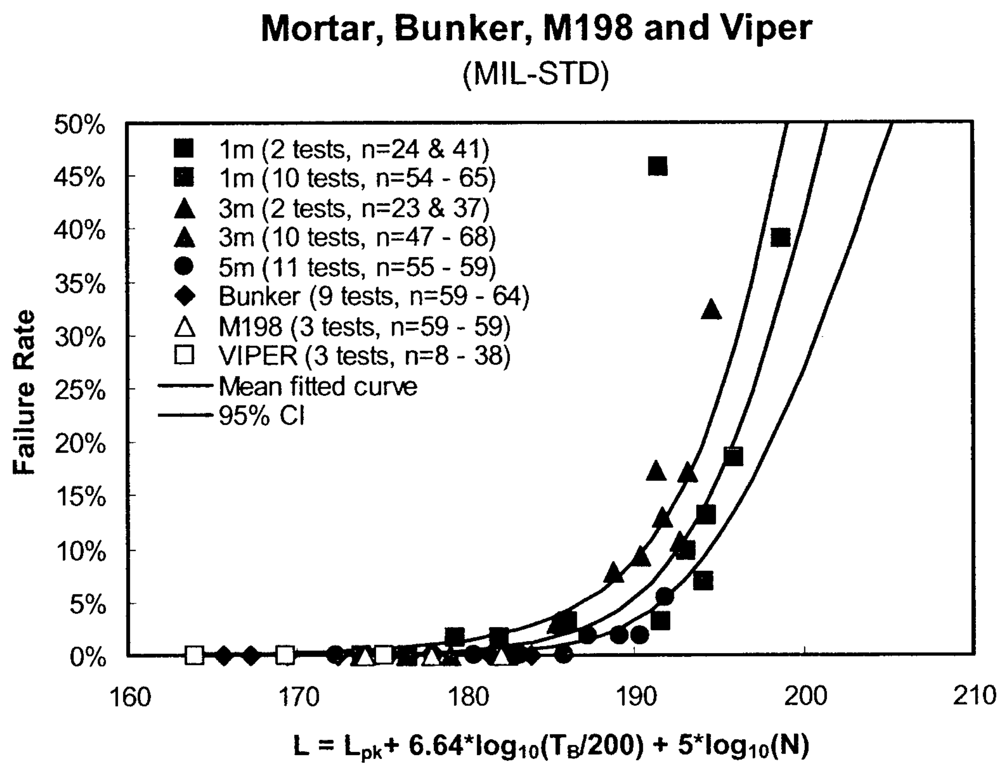


Figure 3. Data comparison with MIL-STD-1474D correlation.

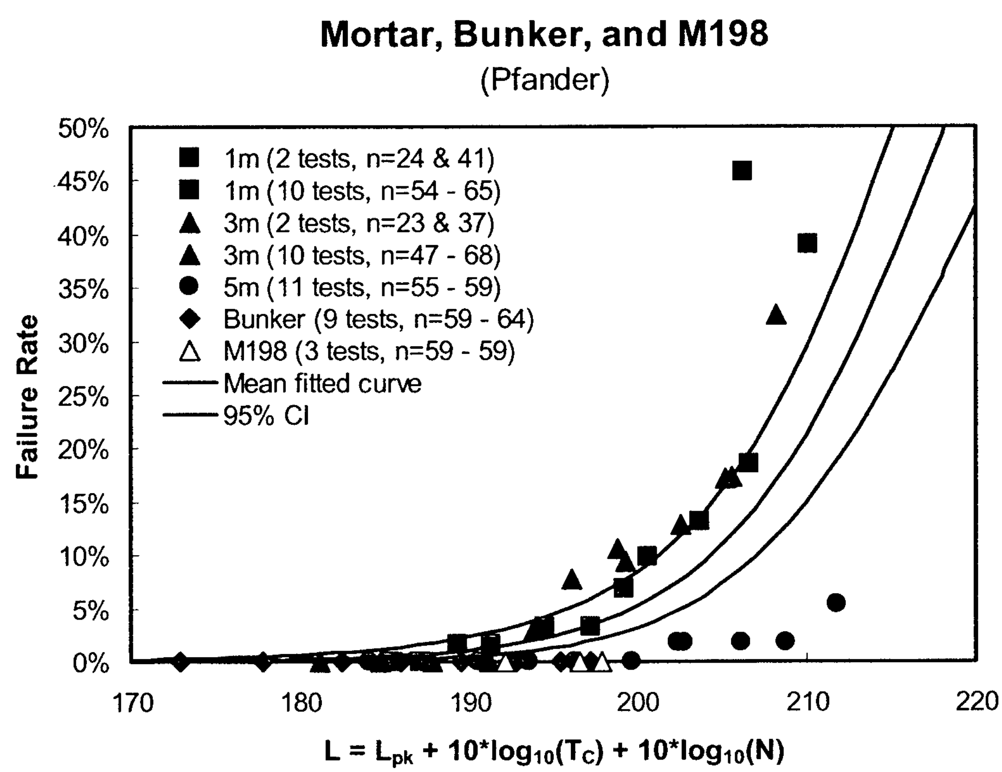


Figure 4. Data comparison with Pfander correlation.

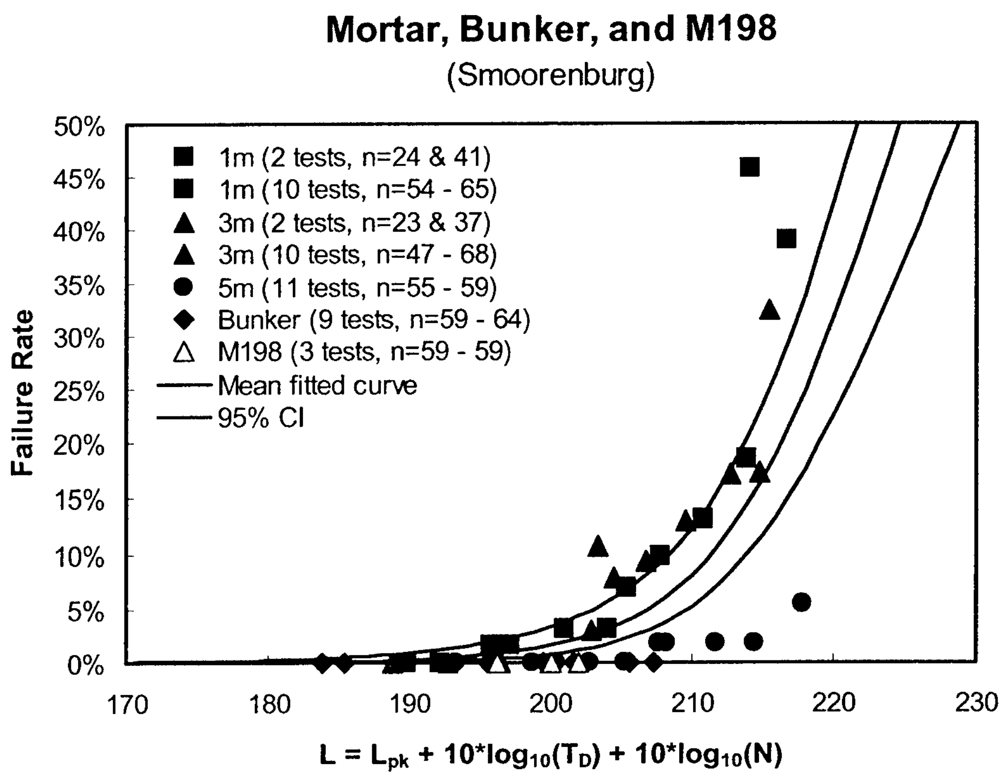


Figure 5. Data comparison with Smoorenburg correlation.

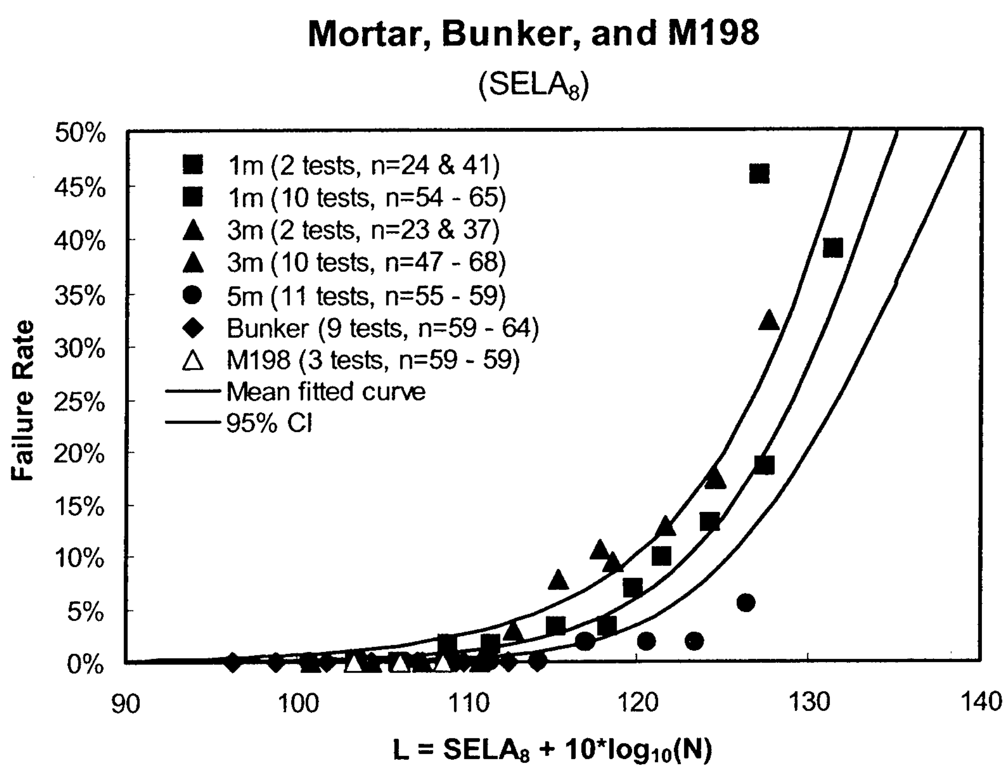


Figure 6. Data comparison with L_{Aeq8} correlation.

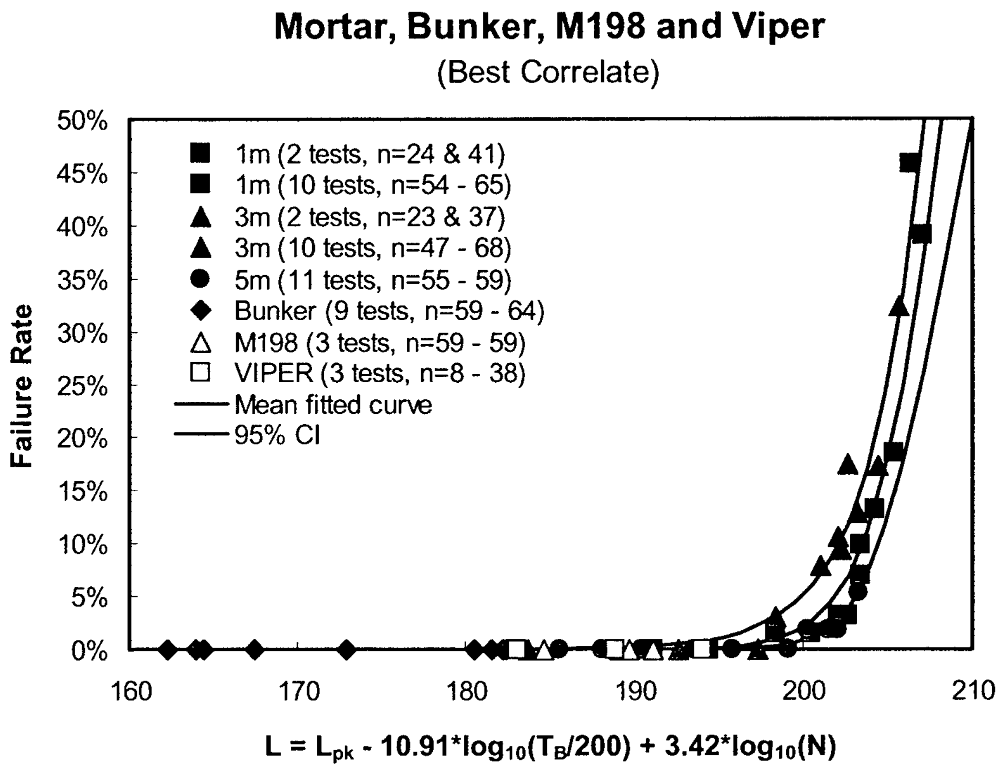


Figure 7. Data comparison with best-fit model.

The conservatism of including the presumed failure data was confirmed by a sensitivity study where the presumed failures were excluded. The logistic regression results without presumed failures are shown in Table 7. Comparison between Tables 6 and 7 indicate that the L(95,95) values for the four criteria and the best-fit model without presumed failures are much higher than with presumed failures. For example, the L(95,95) for MIL-STD will be raised by another 6.6 dB to 193.5 dB, which is 16.5 dB higher than the present limit (Table 7). Therefore, the test data should be analyzed with presumed failures included (Table 6).

Table 7. Logistic Regression Results Without Presumed Failures (All-data-set).

	Thresholds (dB)			
Criteria	Current Limit	L(95,50)	L(95,95)	H-L p-value
MIL-STD-1474D	177	195.7	193.5	0.808
Pfander	189.6	210.1	206.8	0.509
Smoorenburg	191.2	216.1	213.2	0.405
L_{Aeq8}	110	126.6	124.1	0.876
Best-fit model L_{pk}-16.6log(T_B/200)+3.06logN	N/A	208.8	208.0	0.754

To evaluate the usability of chinchilla-based correlates, logistic regressions were performed for the mortar and bunker data using the P, P1, P2 and R weighted energies, SEL_P, SEL_{P1}, SEL_{P2}, and SEL_R, [Hamernik et al., 1998] respectively, with 10logN trading, and the results are shown in Table 8. Presumed failures were included. No records for these four weighted energies are available for the M198 and Viper tests. The L(95,95) values for these four energy correlations are close to one another, ranging from 156.8 to 160.4 dB (Table 8). This is not surprising since these four energy weightings were derived primarily from chinchilla data, with some minor variations. It is believed that the chinchilla ear system is very similar to the human ear. Nevertheless, there are no limits set for these four energies as DRCs for humans. The Hosmer-Lemeshow tests results in p-values generally lower than the NATO criteria (Table 8). The data comparison plots are shown from Figures 8 through 11, indicating trends similar to the four NATO criteria correlations (Figs. 3 through 6). These results suggest that the data from chinchilla tests may be used to gain insights of blast injury trends for the revision of DRC.

Table 8. Logistic Regression Results for P, P1, P2 and R-weighted Energies (Mortar and Bunker).

Correlation	L(95,50) (dB)	L(95,95) (dB)	H-L p-value
SEL_P + 10logN	164.2	159.7	0.159
SEL_{P1} + 10logN	162.1	157.6	0.250
SEL_{P2} + 10logN	161.4	156.8	0.249
SEL_R + 10logN	164.9	160.4	0.366

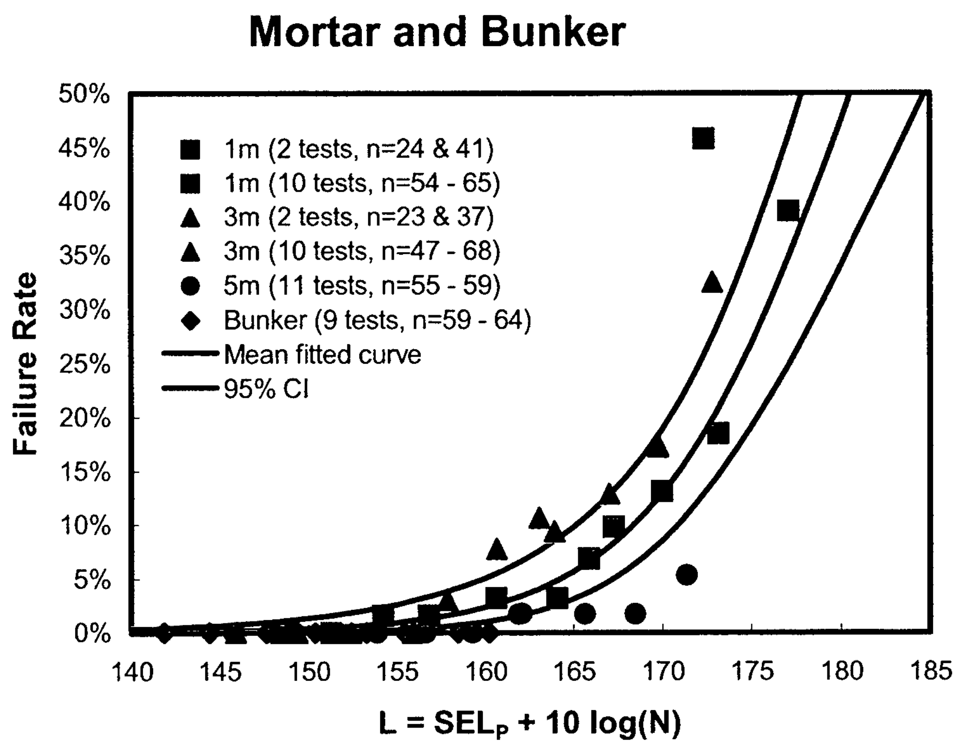


Figure 8. Data comparison for P-weighted energy correlation.

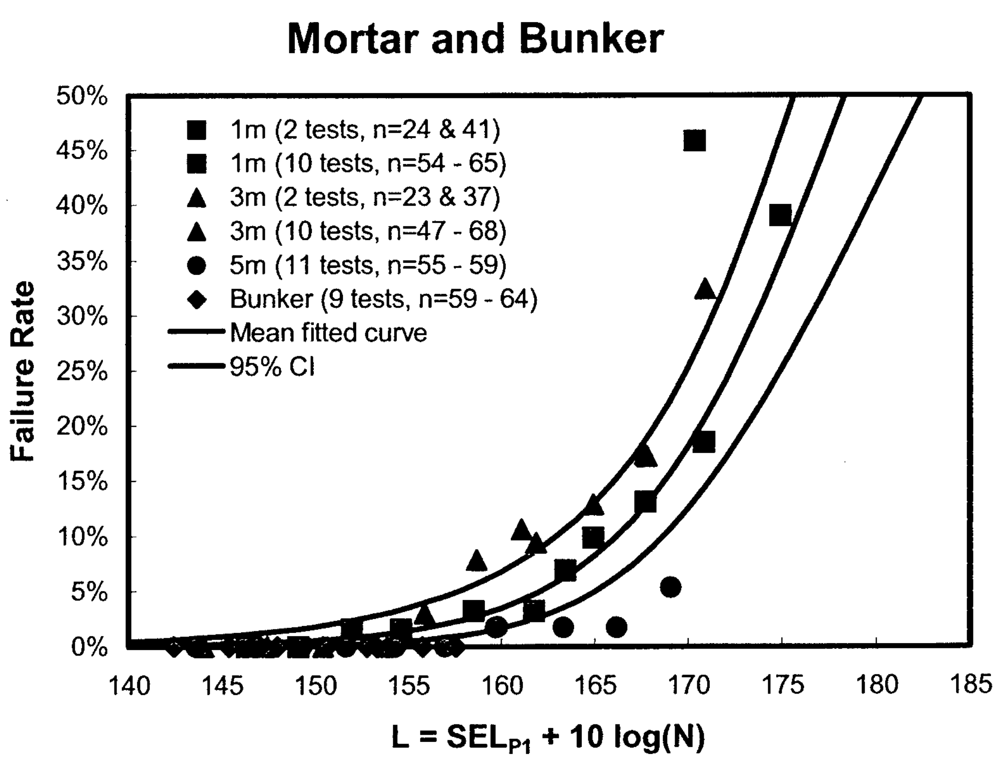


Figure 9. Data comparison for P1-weighted energy correlation.

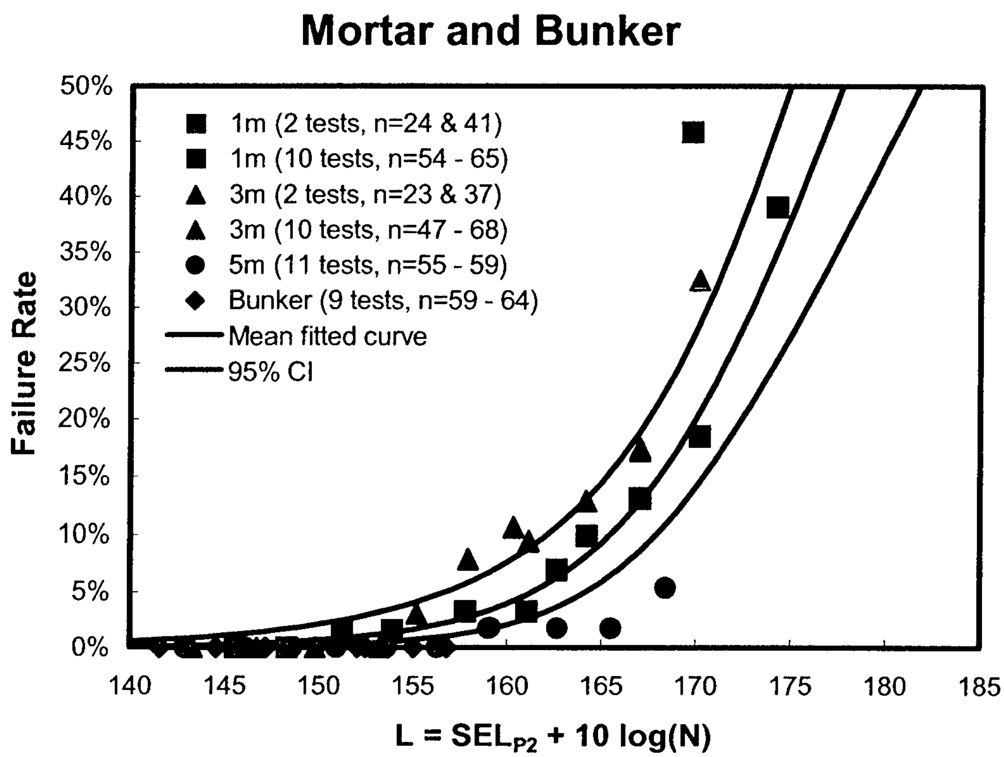


Figure 10. Data comparison for P2-weighted energy correlation.

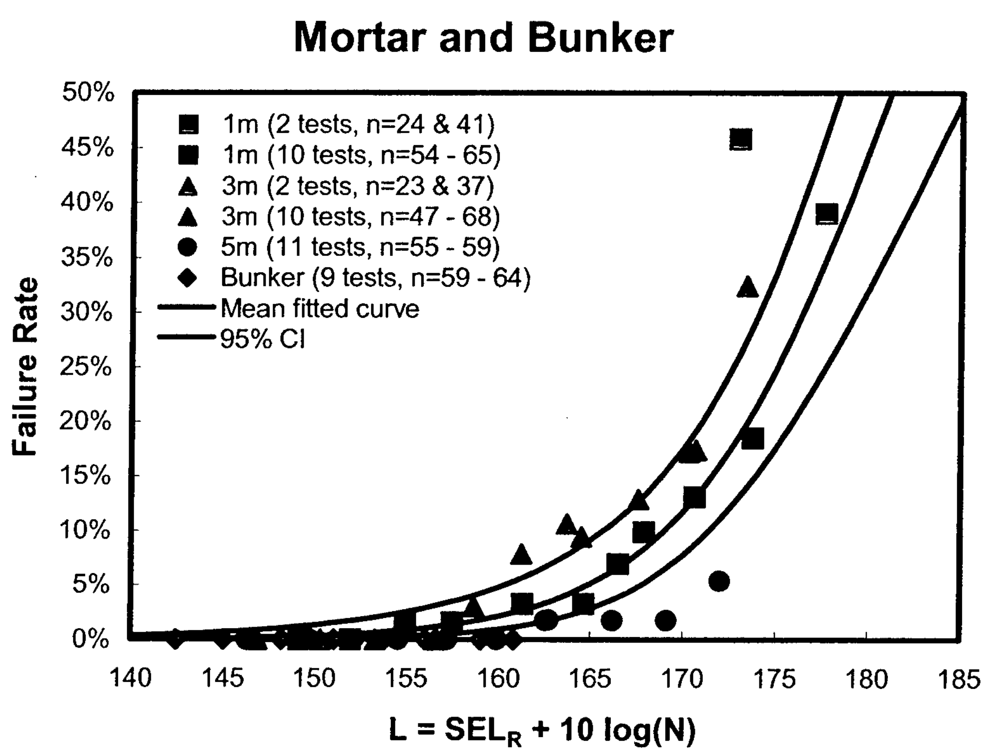


Figure 11. Data comparison for R-weighted energy correlation.

In summary, the regression results show that the protection thresholds for the four DRCs can be raised by 4-12 dB (Table 6). For MIL-STD-1474D, based on the subjects wearing single hearing protection, and this collection of blast waves as tested, 95% protection against TTS $\geq$ 25 dB with 95% confidence can be achieved for $L_M \leq 186.9$ dB, which is 9.9 dB above the current value (Table 6). Similarly, the limits for Pfander, Smoorenburg and L_{Aeq8} can be raised to 195.9, 203.2 and 114.7 dB, respectively.

4. DISCUSSION

The objective of the present work is to evaluate the four given NATO criteria for impulse noise against the data from human exposure tests. The data was pooled to gain the maximum statistical power. The thresholds for each criteria and the confidence bands were determined in statistical analysis guided by recognized experts in the field. In addition, a criterion using peak, T_B and N was fitted to yield a L(95,95) threshold that also resulted in the best goodness-of-fit (Table 6).

The L_{Aeq8} threshold is the "closest" to the calculated L(95,95), differing by 4.7 dB (Table 6). However, this comparison can only be considered qualitative because the four effective levels defined by the four criteria cannot be compared with one another in absolute sense (Table 1). That is, a dB difference in A-weighted energy is not the same as a dB difference for the effective exposure levels defined by the other three criteria.

The "conventional wisdom" that assumes that hearing protection reduces levels by 25 dB may not be adequate. Other research has indicated hearing protectors are sensitive to both intensity levels as well as spectral effects [Dancer et al., 1992]. However, no rule has been established to correlate ear canal pressures to injury based on actual human volunteer tests. The present approach is consistent with the on-going practice of using free field pressure for field applications.

The change of the N-trading rule by the best fit model indicates that the study of N-trading by fixing the other parameter coefficients may be of limited use and may lead to misleading conclusions in the discussion of so-called "equal energy hypothesis." The coefficients for N should be optimized together with the other parameter coefficients in the way the best-fit model was determined in the present work. The present best-fit model (Table 6) is still peak and duration-based and has not been tested against other data sets. Nevertheless, the negative coefficient for T_B suggests that longer pulses are less hazardous, which is contrary to all duration-based criteria. This indicates that spectral effects are still not fully captured by peak and duration-based methods.

The four available data sets analyzed do not address the issues of variable presentation rates for multiple shots or the effects of the combination of different blast waves with different peak and durations. Previous work on this issue has been limited [Patterson, 1997]. It may appear that the energy-based L_{Aeq8} method may be more appropriate for these complex exposure conditions, but much more validation work is still required.

It is realized that other data sets have not been included because of the lack of uniformity. Many other data sets did not define injury as TTS $\geq$ 25 dB at 2 min, and some tests used the recovery time as a failure measure [Pfander et al., 1980 and Dancer et al., 1991]. Furthermore, in order for any other data set to be included, the original subject test matrix and pass/fail data are needed so that injury thresholds can be evaluated with consistent statistical analysis, and that is usually not the case.

The current MIL-STD-1474D for single hearing protection was found to be about 9.9 dB below the L(95,95) threshold for observed injury in the tested subject group. This result is consistent with the findings of previous man-rating studies and helps quantify the amount of conservatism in the standard. Since the sample size is small, the pressure waves come from a limited class of blasts, and the test population may be better fitted with hearing protection, there must be judgment exercised in deciding how much the standard can be increased.

ACKNOWLEDGEMENT

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APPENDIX.

BOP Data Preparation

The BOP data from EG&G were delivered to Jaycor through USAMRMC for analysis. The data contain pressure traces, subject auditory outcomes and calculated waveform parameters. The EG&G data are considered to be complete. The CD-ROMs containing the data from EG&G are as follows:

Table A-1. Data CDs from EG&G.

No.	Title	Volumes
1	Final Task Report: DAMD-17-88-C-8141	1
2	Final Task Report: Audiometric and Other Data	2
3	Final Task Report: Blast Waveforms, 5-m Distance	3
4	Final Task Report: Blast Waveforms, 1-m Distance	3
5	Final Task Report: Blast Waveforms, 3-m Distance	3
6	ISL Artificial Head Data	1
7	Final Task Report: DAMD-17-93-C-3101	1
8	Final Task Report: DAMD-17-93-C-3101, Addendum No.1	1
9	Final Task Report: Task Order 2, 4, and 5	1
10	Final Task Report: Task Order 2, 4, and 5, Blast Data	3
11	Test Logbooks	1
12	Data Analysis Software	1
13	Bunker Study: Test Blast Data	1
14	Nonlinear Earplug Study: Test Blast Data	1
15	Under Ear Muffs Study: Blast Data and Data Base	1

A subset of the test data were taken and processed by USAARL, including pressure data measured under the earmuff. One data CD was received separately from USAARL.

The final data set for analysis was obtained from the EG&G pressure traces and the subject walk-up matrices. The USAARL data were used for cross checking. Furthermore, some data traces with calculated waveform parameters printed out at the test site were available and were used selectively for cross checking.

Mortar (Free Field) Tests

All the free field data from EG&G for the Mortar tests using modified muffs needed for criteria evaluation were screened with bad traces eliminated. All together 60,007 traces were analyzed. For the Mortar tests, only data from studies M, D, and C using the modified muff were used for criteria evaluation, totaling 39,910 traces (Table A-2).

Table A-2. Mortar Test Free Field Data Verification.

Study	Code	Period	Total Traces	Bad Traces
5 m, modified muff	M	08/90 – 06/91	11,368	1,845
1 m, modified muff	D	07/91 – 05/92	16,016	55
3 m, modified muff	C	06/92 – 04/93	15,420	994
Total:			42,804	2,894

The sampling rate for the data traces was determined to be 250,000 per second. The sampling rate was confirmed with selected cross comparison of the EG&G data with those from USAARL as well as printed records archived at the test site showing the pressure trace and A-duration.

Two steps were followed to eliminate bad traces: (1) visual checking, and (2) evaluation of the pressure peak mean values and standard deviations.

Each trace was first screened visually for unusual spikes and/or behaviors, such as obvious drifts and erratic pattern, where the trace would be tagged as "bad" and not included for further statistical evaluation.

The traces were further screened by analyzing the standard deviation of the peak values. For each test condition, that is for a selected distance at a given level, the mean peak value and the standard deviation were calculated for the entire group of subjects, for each subgroup, as well as for each gauge. The test group size ranged from 24-68 people while each subgroup consisted of mostly 6 subjects being exposed to a blast each time where four gauges were usually used to record incident pressures. It was found that if the standard deviation exceeded 3 dB, it was caused by some unusual gauge behavior, such as abnormal spikes, erratic drifts and noise. These gauges were then tagged as bad and eliminated from statistical average calculations. It was also found that a bad gauge always behaved "bad" consistently. When the bad gauges were excluded, the standard deviation was mostly within 2 dB. As shown in Table A-2, less than 7% of the gauges was considered bad.

All the waveform parameters needed for criteria analysis were computed for each trace. These parameters are the peak, A-duration, B-duration, C-duration, D-duration, linear energy, A-weighted energy, P-weighted energy, P1-weighted energy, P2-weighted energy, and R-weighted energy. Generally, the standard deviations for the peak and the various energy values are less than 2% of their respective mean values. The standard deviations for the various durations, especially, the B and D-durations, can exceed 10% of their respective mean values.

Jaycor's calculated waveform parameters compare closely with those from the USAARL database that was derived from a subset of all the data. In particular, the peaks and energies between the Jaycor and USAARL calculations are close to one another. For B-duration, Jaycor's calculations are usually slightly greater than the USAARL values, but the effect on the MIL-STD effective exposure level is insignificant. We used the B-duration algorithms delivered to us by EG&G. Jaycor's calculated waveform parameters, however, could not be compared against those from the EG&G Mortar test database since the latter shows inconsistent data entries.

The injury data were traced from the walk-up matrices for all subjects found in the EG&G final report [Johnson, 1994]. Some minor inconsistencies between the walk-up matrices and the summarized injury results in the EG&G report could not be resolved, and we took the walk-up matrices as the final data.

Table A-3 shows the derived injury data for the Mortar test at 1m, where each number in a test box refers to a particular subject, and the conditional, observed and presumed failures are indicated by different colors. Table A-4 shows only the conditional and observed failures. Table A-5 shows the cross-reference between the assigned subject number and the actual subject identification (ID) in the test.

Similarly, Table A-6 presents the derived injury data for the Mortar test at 3m, and Table A-7 presents only the conditional and observed failures, with the subject cross-reference found in Table A-8. Likewise, Tables A-9 to A-11 present the data for the 5m test.

Table A-3. Derived Injury Data for Mortar 1-m Test.

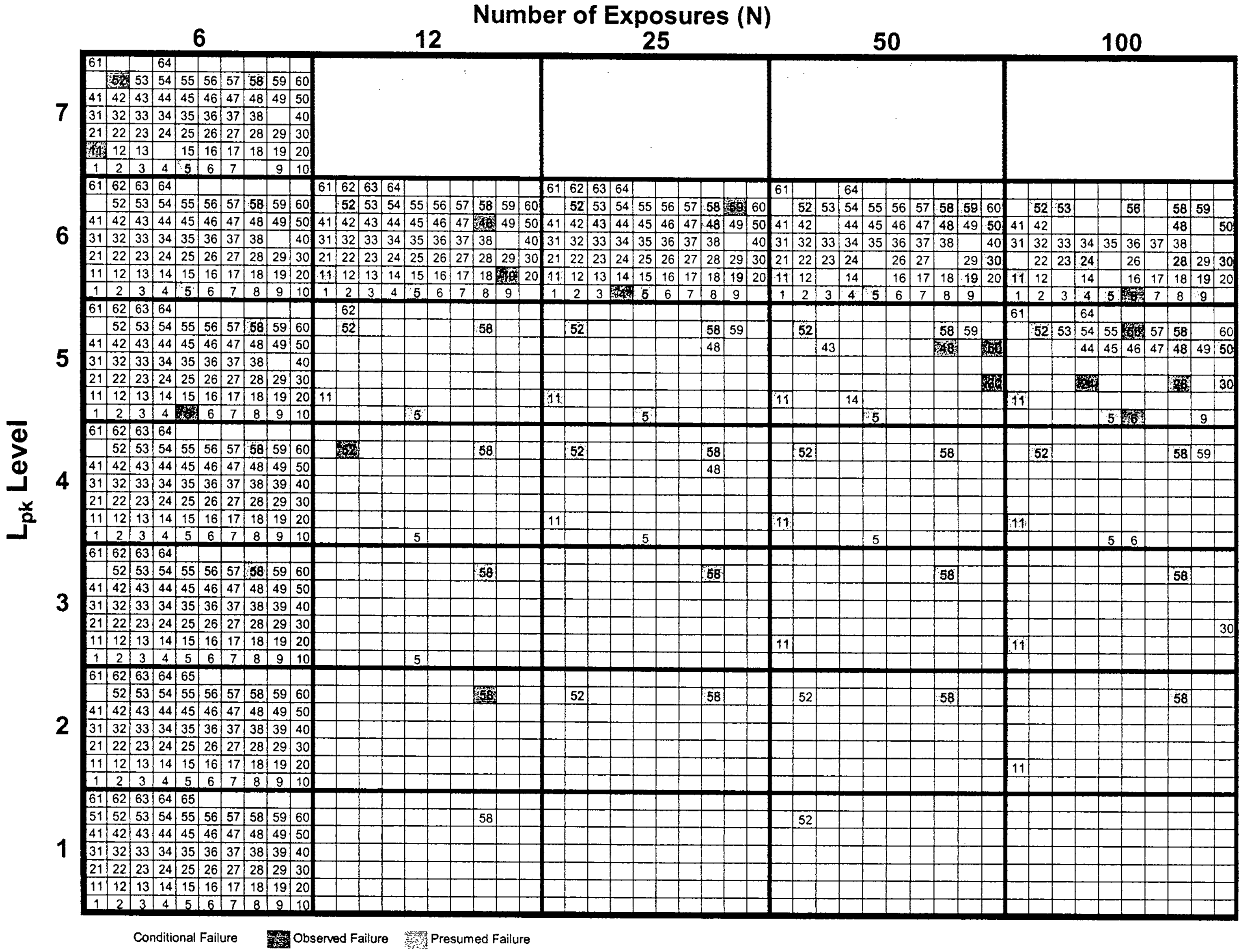

Table A-4. Observed Injury Data for Mortar 1-m Test.

Number of Exposures (N)

N = 6

L_{pk} Level										
7	61			64						
		52	53	54	55	56	57		59	60
	41	42	43	44	45	46	47	48	49	50
	31	32	33	34	35	36	37	38		40
	21	22	23	24	25	26	27	28	29	30
	11	12	13		15	16	17	18	19	20
	1	2	3	4		6	7		9	10
6	61	62	63	64						
		52	53	54	55	56	57		59	60
	41	42	43	44	45	46	47	48	49	50
	31	32	33	34	35	36	37	38		40
	21	22	23	24	25	26	27	28	29	30
	11	12	13	14	15	16	17	18	19	20
	1	2	3	4		6	7	8	9	10
5	61	62	63	64						
		52	53	54	55	56	57		59	60
	41	42	43	44	45	46	47	48	49	50
	31	32	33	34	35	36	37	38		40
	21	22	23	24	25	26	27	28	29	30
	11	12	13	14	15	16	17	18	19	20
	1	2	3	4	**5**	6	7	8	9	10
4	61	62	63	64						
		52	53	54	55	56	57		59	60
	41	42	43	44	45	46	47	48	49	50
	31	32	33	34	35	36	37	38	39	40
	21	22	23	24	25	26	27	28	29	30
	11	12	13	14	15	16	17	18	19	20
	1	2	3	4	5	6	7	8	9	10
3	61	62	63	64						
		52	53	54	55	56	57		59	60
	41	42	43	44	45	46	47	48	49	50
	31	32	33	34	35	36	37	38	39	40
	21	22	23	24	25	26	27	28	29	30
	11	12	13	14	15	16	17	18	19	20
	1	2	3	4	5	6	7	8	9	10
2	61	62	63	64	65					
		52	53	54	55	56	57	58	59	60
	41	42	43	44	45	46	47	48	49	50
	31	32	33	34	35	36	37	38	39	40
	21	22	23	24	25	26	27	28	29	30
	11	12	13	14	15	16	17	18	19	20
	1	2	3	4	5	6	7	8	9	10
1	61	62	63	64	65					
	51	52	53	54	55	56	57	58	59	60
	41	42	43	44	45	46	47	48	49	50
	31	32	33	34	35	36	37	38	39	40
	21	22	23	24	25	26	27	28	29	30
	11	12	13	14	15	16	17	18	19	20
	1	2	3	4	5	6	7	8	9	10

N = 12

L_{pk} Level										
7										
6	61	62	63	64						
			53	54	55	56	57		59	60
	41	42	43	44	45	46	47	**48**	49	50
	31	32	33	34	35	36	37	38		40
	21	22	23	24	25	26	27	28	29	30
		12	13	14	15	16	17	18	**19**	20
	1	2	3	4		6	7	8	9	
5		62								
	11									
4										
		52								
					5					
3										
					5					
2										
								58		
1										
								58		

N = 25

L_{pk} Level										
7										
6	61	62	63	64						
			53	54	55	56	57		**59**	60
	41	42	43	44	45	46	47		49	50
	31	32	33	34	35	36	37	38		40
	21	22	23	24	25	26	27	28	29	30
		12	13	14	15	16	17	18		20
	1	2	3	**4**		6	7	8	9	
5										
									59	
								48		
4										
								48		
	11									
					5					
3										
2										
		52								
1										

N = 50

L_{pk} Level										
7										
6	61			64						
			53	54	55	56	57			60
	41	42		44	45	46	47		49	
	31	32	33	34	35	36	37	38		40
	21	22	23	24		26	27		29	
		12		14		16	17	18		20
	1	2	3			6	7	8	9	
5										
									59	
			43					**48**		**50**
										30
				14						
4										
					5					
3										
	11									
2										
		52								
1										
		52								

N = 100

L_{pk} Level										
7										
6										
	41	42								
	31	32	33	34	35	36	37	38		
		22	23			26			29	
		12		14		16	17	18		20
	1	2	3			**6**	7	8		
5	61			64						
			53	54	55	**56**	57			60
				44	45	46	47		49	
				24				**28**		
						6			9	
4										
									59	
					5	6				
3										
										30
2										
	11									
1										

Conditional Failure   Observed Failure

Table A-5. Subject Cross Reference for Mortar 1-m Test.

Subject Number	Subject ID
1	DAA1
2	DAA2
3	DAA3
4	DAA4
5	DAA5
6	DAB1
7	DAB4
8	DBC1
9	DBC2
10	DBC3
11	DBC4
12	DBC5
13	DBC6
14	DBD1
15	DBD2
16	DBD3
17	DBD4
18	DBD5
19	DBD6
20	DCE1
21	DCE2
22	DCE3
23	DCE4
24	DCE5
25	DCE6
26	DCF1
27	DCF2
28	DCF3
29	DCF4
30	DCF5
31	DCF7
32	DDG3
33	DDG4
34	DDG5
35	DDG7
36	DDG8
37	DDH1
38	DDH2
39	DDH3
40	DDH4
41	DDH5
42	DDH6
43	DEI1
44	DEI2
45	DEI3
46	DEI4
47	DEI5
48	DEI7
49	DEJ2
50	DEJ3
51	DEJ4
52	DEJ5
53	DEJ6
54	DFK1
55	DFK2
56	DFK3
57	DFK4
58	DFK5
59	DFK6
60	DFL1
61	DFL2
62	DFL3
63	DFL4
64	DFL5
65	DFL6

Table A-6. Derived Injury Data for Mortar 3-m Test.

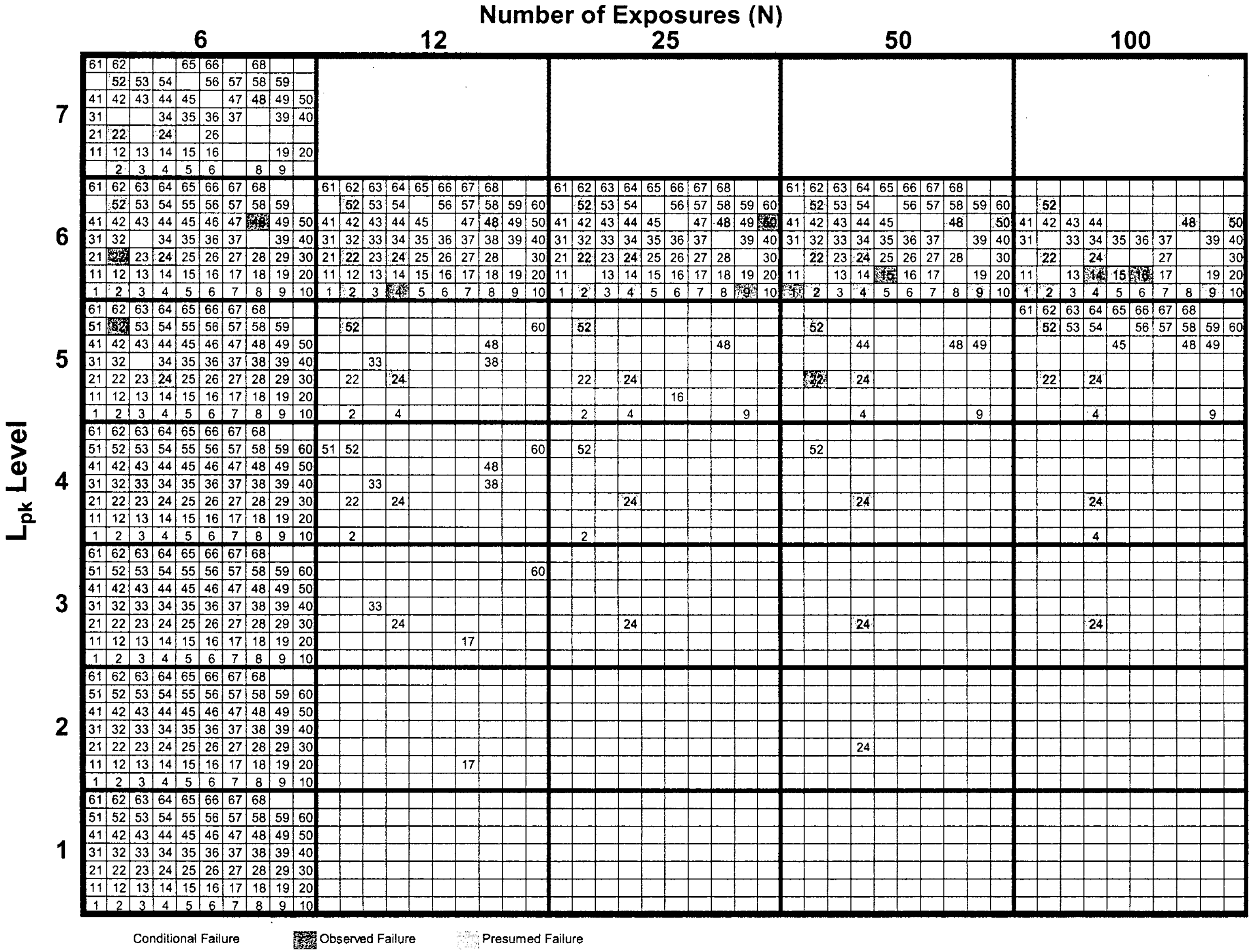

Table A-7. Observed Injury Data for Mortar 3-m Test.

Number of Exposures (N)

N = 6

L_{pk} Level										
	61	62			65	66		68		
			53	54		56	57	58	59	
	41	42	43	44	45		47		49	50
7	31			34	35	36	37		39	40
	21					26				
	11	12	13	14	15	16			19	20
			3	4	5	6		8	9	
	61	62	63	64	65	66	67	68		
			53	54	55	56	57	58	59	
	41	42	43	44	45	46	47	**48**	49	50
6	31	32		34	35	36	37		39	40
	21	**22**	23		25	26	27	28	29	30
	11	12	13	14	15	16	17	18	19	20
	1		3	4	5	6	7	8	9	10
	61	62	63	64	65	66	67	68		
	51	**52**	53	54	55	56	57	58	59	
	41	42	43	44	45	46	47	48	49	50
5	31	32		34	35	36	37	38	39	40
	21	22	23		25	26	27	28	29	30
	11	12	13	14	15	16	17	18	19	20
	1	2	3	4	5	6	7	8	9	10
	61	62	63	64	65	66	67	68		
	51	52	53	54	55	56	57	58	59	60
	41	42	43	44	45	46	47	48	49	50
4	31	32	33	34	35	36	37	38	39	40
	21	22	23	24	25	26	27	28	29	30
	11	12	13	14	15	16	17	18	19	20
	1	2	3	4	5	6	7	8	9	10
	61	62	63	64	65	66	67	68		
	51	52	53	54	55	56	57	58	59	60
	41	42	43	44	45	46	47	48	49	50
3	31	32	33	34	35	36	37	38	39	40
	21	22	23	24	25	26	27	28	29	30
	11	12	13	14	15	16	17	18	19	20
	1	2	3	4	5	6	7	8	9	10
	61	62	63	64	65	66	67	68		
	51	52	53	54	55	56	57	58	59	60
	41	42	43	44	45	46	47	48	49	50
2	31	32	33	34	35	36	37	38	39	40
	21	22	23	24	25	26	27	28	29	30
	11	12	13	14	15	16	17	18	19	20
	1	2	3	4	5	6	7	8	9	10
	61	62	63	64	65	66	67	68		
	51	52	53	54	55	56	57	58	59	60
	41	42	43	44	45	46	47	48	49	50
1	31	32	33	34	35	36	37	38	39	40
	21	22	23	24	25	26	27	28	29	30
	11	12	13	14	15	16	17	18	19	20
	1	2	3	4	5	6	7	8	9	10

N = 12

L_{pk} Level										
7										
	61	62	63	64	65	66	67	68		
			53	54		56	57	58	59	60
	41	42	43	44	45		47		49	50
6	31	32	33	34	35	36	37	38	39	40
	21		23		25	26	27	28		30
	11	12	13	14	15	16	17	18	19	20
	1		3	**4**	5	6	7	8	9	10
										60
								48		
5			33					38		
		22								
		2		4						
	51	52								60
								48		
4			33					38		
		22		24						
		2								
										60
3			33							
				24						
							17			
2										
							17			
1										

N = 25

L_{pk} Level										
7										
	61	62	63	64	65	66	67	68		
			53	54		56	57	58	59	60
	41	42	43	44	45		47		49	**50**
6	31	32	33	34	35	36	37		39	40
	21		23		25	26	27	28		30
	11		13	14	15	16	17	18	19	20
	1		3		5	6	7	8	**9**	10
								48		
5										
		22								
						16				
		2		4					9	
		52								
4										
		2								
3										
				24						
2										
1										

N = 50

L_{pk} Level										
7										
	61	62	63	64	65	66	67	68		
			53	54		56	57	58	59	60
	41	42	43	44	45					
6	31	32	33	34	35	36	37		39	40
			23		25	26	27	28		30
	11		13	14	**15**	16	17		19	20
	1		3		5	6	7	8		10
				44				48	49	
5										
		22								
				4					9	
		52								
4										
3										
				24						
2										
1										

N = 100

L_{pk} Level										
7										
	41	42	43	44						
6	31		33	34	35	36	37		39	40
							27			30
	11		13	**14**		**16**	17		19	20
			3		5	6	7	8		10
	61	62	63	64	65	66	67	68		
			53	54		56	57	58	59	60
					45			48	49	
5										
									9	
4										
				4						
3										
2										
1										

Conditional Failure

Observed Failure

Table A-8. Subject Cross Reference for Mortar 3-m Test.

Subject Number	Subject ID	Subject Number	Subject ID
1	CAA3	36	CDG6
2	CAA4	37	CEH1
3	CAA5	38	CEH2
4	CAA6	39	CEH3
5	CAB1	40	CEH4
6	CAB2	41	CEH5
7	CAB3	42	CEI2
8	CAB4	43	CEI3
9	CAB5	44	CEI4
10	CAB6	45	CFJ2
11	CAB7	46	CFJ3
12	CBC1	47	CFJ4
13	CBC2	48	CFJ5
14	CBC3	49	CFJ6
15	CBC4	50	CFJ7
16	CBC5	51	CFK1
17	CBC6	52	CFK2
18	CCD1	53	CFK3
19	CCD3	54	CFK5
20	CCD4	55	CFK6
21	CCD5	56	CFK7
22	CCE1	57	CGL1
23	CCE2	58	CGL2
24	CCE3	59	CGL3
25	CCE4	60	CGL4
26	CCE5	61	CGL5
27	CDF2	62	CGL6
28	CDF3	63	CGM1
29	CDF4	64	CGM2
30	CDF5	65	CGM3
31	CDG1	66	CGM4
32	CDG2	67	CGM5
33	CDG3	68	CGM6
34	CDG4		
35	CDG5		

Table A-9. Derived Injury Data for Mortar 5-m Test.

Number of Exposures (N): 6, 12, 25, 50, 100 — rows: L_{pk} Level 7 to 1

L_{pk} Level 7, N = 6

51	52	53	54	55	56	57		59	
41	42	43	44	45	46	47		49	50
31	32	33	34	35	36	37	38	39	40
21	22	23	24	25	26	27	28	29	
11		13	14	15	16	17	18	19	20
1	2	3	4	5	6	7	8	9	10

L_{pk} Level 6, N = 6, 12, 25, 50

51	52	53	54	55	56	57		59	
41	42	43	44	45	46	47	48	49	50
31	32	33	34	35	36	37	38	39	40
21	22	23	24	25	26	27	28	29	
11	12	13	14	15	16	17	18	19	20
1	2	3	4	5	6	7	8	9	10

L_{pk} Level 6, N = 100

51	52	53	54	55	56	57		59	
41	42		44	45	46	47	48	49	50
31	32	33	34	35	36	37	38	39	40
21	22	23	24	25	26	27	28	29	
11	12	13	14	15	16	17	18	19	20
1	2	3	4	5	6	7	8	9	10

L_{pk} Level 5, N = 6

51	52	53	54	55	56	57		59	
41	42	43	44	45	46	47	48	49	50
31	32	33	34	35	36	37	38	39	40
21	22	23	24	25	26	27	28	29	
11	12	13	14	15	16	17	18	19	20
1	2	3	4	5	6	7	8	9	10

L_{pk} Level 5, N = 12, 25, 50, 100

N	Row 41	Row 31	Row 1
12	46		
25	46	38	
50	46		
100	46		4

L_{pk} Level 4, N = 6

51	52	53	54	55	56	57		59	
41	42	43	44	45	46	47	48	49	50
31	32	33	34	35	36	37	38	39	40
21	22	23	24	25	26	27	28	29	30
11	12	13	14	15	16	17	18	19	20
1	2	3	4	5	6	7	8	9	10

L_{pk} Level 4, N = 12, 25, 50, 100

N	Row 41
12	46
25	46
50	46
100	46

L_{pk} Level 3, N = 6

51	52	53	54	55	56	57	58	59	
41	42	43	44	45	46	47	48	49	50
31	32	33	34	35	36	37	38	39	40
21	22	23	24	25	26	27	28	29	30
11	12	13	14	15	16	17	18	19	20
1	2	3	4	5	6	7	8	9	10

L_{pk} Level 3, N = 50, 100

N	Row 41
50	46
100	46

L_{pk} Level 2, N = 6

51	52	53	54	55	56	57	58	59	
41	42	43	44	45	46	47	48	49	50
31	32	33	34	35	36	37	38	39	40
21	22	23	24	25	26	27	28	29	30
11	12	13	14	15	16	17	18	19	20
1	2	3	4	5	6	7	8	9	10

L_{pk} Level 2, N = 100

N	Row 41
100	46

L_{pk} Level 1, N = 6

51	52	53	54	55	56	57	58	59	
41	42	43	44	45	46	47	48	49	50
31	32	33	34	35	36	37	38	39	40
21	22	23	24	25	26	27	28	29	30
11	12	13	14	15	16	17	18	19	20
1	2	3	4	5	6	7	8	9	10

Conditional Failure — Observed Failure — Presumed Failure

Table A-10. Observed Injury Data for Mortar 5-m Test.

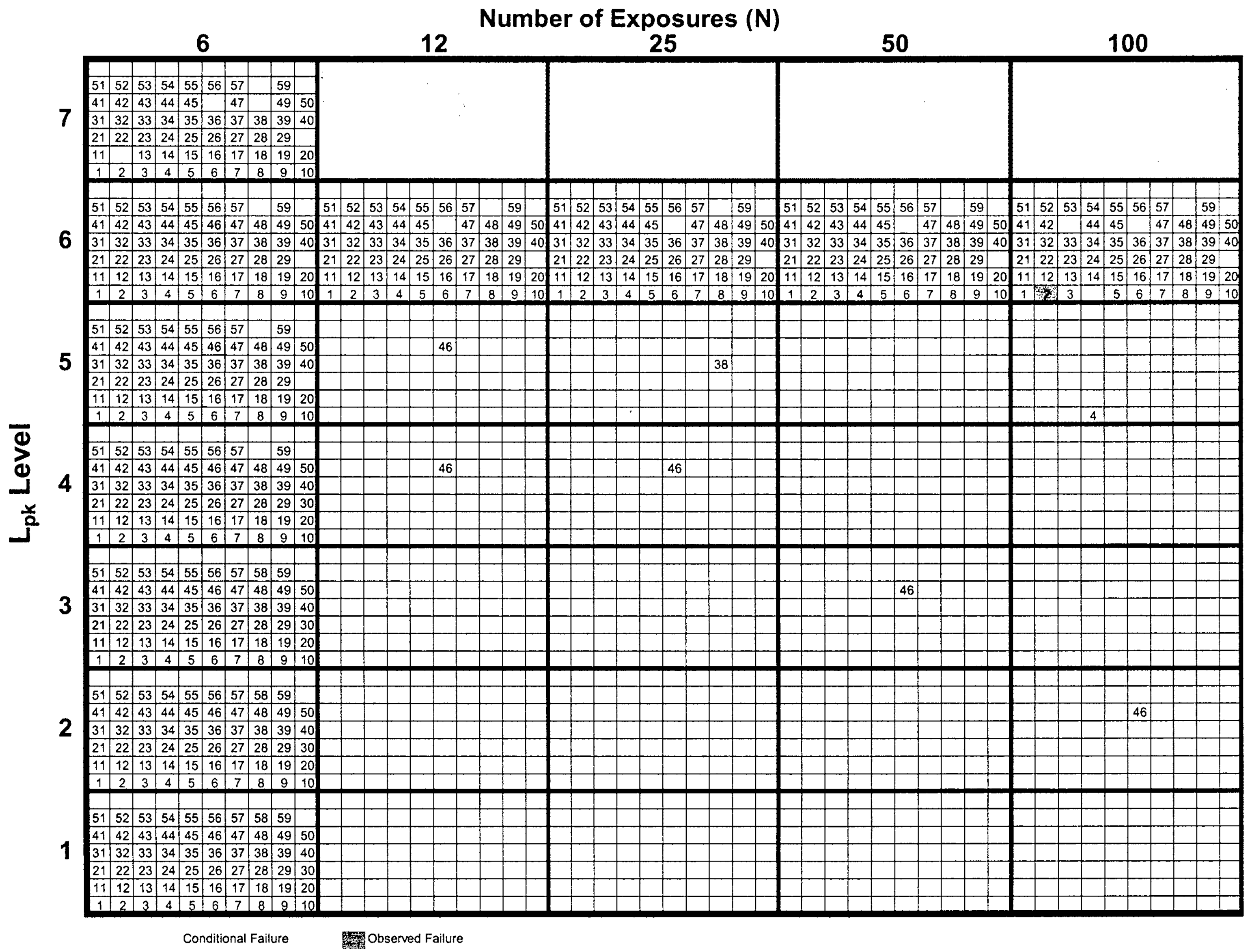

Table A-11. Subject Cross Reference for Mortar 5-m Test.

Subject Number	Subject ID	Subject Number	Subject ID
1	MAA1	36	MDG4
2	MAA2	37	MDG6
3	MAA3	38	MEH1
4	MAA4	39	MEH3
5	MAA5	40	MEH4
6	MAB2	41	MEH5
7	MAB3	42	MEH6
8	MAB4	43	MEI1
9	MAB5	44	MEI3
10	MBC1	45	MEI4
11	MBC2	46	MEI5
12	MBC3	47	MEI6
13	MBC4	48	MFJ1
14	MBC5	49	MFJ2
15	MBC6	50	MFJ3
16	MBD1	51	MFJ4
17	MBD2	52	MFJ5
18	MBD3	53	MFJ6
19	MBD4	54	MFK1
20	MBD5	55	MFK2
21	MBD6	56	MFK4
22	MCE1	57	MFK5
23	MCE2	58	MFK6
24	MCE3	59	MFK7
25	MCE4		
26	MCE5		
27	MCE6		
28	MCF1		
29	MCF2		
30	MCF3		
31	MCF4		
32	MCF5		
33	MDG1		
34	MDG2		
35	MDG3		

Bunker Tests

The bunker calibration data were screened in a similar fashion as the Mortar data as described above. Only calibration data were used for criteria evaluation because no free field data at the subject locations were taken during the actual tests. There were only 569 traces for the bunker calibration tests, for 7 levels with 1, 2 and 3 shots. Only wall gauge data were taken during the actual tests. The calibration tests were conducted after the human tests were finished. Our analysis shows that the bunker "free field" data reported in the USAARL database were actually wall gauge data.

Our calculated waveform parameters for the bunker calibration data agree closely with those from the EG&G database, except for the linear and A-weighted energies. After cross-checking with the USAARL data, we concluded that the energies recorded in the EG&G bunker database were consistently about 7 dB too low. The mean peak values for the screened calibration data are close to those shown in the EG&G final report within 2 dB.

The subject failure data and cross-reference for the Bunker test are shown in Tables A-12 and A-13, respectively.

Table A-12. Injury Data for Bunker Test.

L_{pk} Level	Number of Exposures (N): 1										2										3									
	61	62	63	64																										
	51	52	53	54	55	56	57	58	59	60																				
	41	42	43	44	45	46	47		49	50																				
7	31	32	33	34	35	36	37		39	40																				
	21	22	23	24	25	26	27	28	29	30																				
		12	13		15	16	17	18	19	20																				
	1	2	3	4	5	6	7	8		10																				
	61	62	63	64							61	62	63	64							61	62	63	64						
	51	52	53	54	55	56	57	58	59	60	51	52	53	54	55	56	57	58	59	60	51	52	53	54	55	56	57	58	59	60
	41	42	43	44	45	46	47		49	50	41	42	43	44	45	46	47		49	50	41	42	43	44	45	46	47		49	50
6	31	32	33	34	35	36	37		39	40	31	32	33	34	35	36	37		39	40	31	32	33	34	35	36	37		39	40
	21	22	23	24	25	26	27	28	29	30	21	22	23	24	25	26	27	28	29	30	21	22	23	24	25	26	27	28	29	30
		12	13		15	16	17	18	19	20		12	13		15	16	17	18	19	20		12	13		15	16	17	18	19	20
	1	2	3	4	5	6	7	8		10	1	2	3	4	5	6	7	8		10	1	2	3	4	5	6	7	8		10
	61	62	63	64																										
	51	52	53	54	55	56	57	58	59	60																				
	41	42	43	44	45	46	47	48	49	50																				
5	31	32	33	34	35	36	37		39	40																				
	21	22	23	24	25	26	27	28	29	30																				
		12	13	14	15	16	17	18	19	20																				
	1	2	3	4	5	6	7	8		10																				
	61	62	63	64																										
	51	52	53	54	55	56	57	58	59	60																				
	41	42	43	44	45	46	47	48	49	50																				
4	31	32	33	34	35	36	37		39	40																				
	21	22	23	24	25	26	27	28	29	30																				
		12	13	14	15	16	17	18	19	20																				
	1	2	3	4	5	6	7	8		10																				
	61	62	63	64																										
	51	52	53	54	55	56	57	58	59	60																				
	41	42	43	44	45	46	47	48	49	50																				
3	31	32	33	34	35	36	37	38	39	40																				
	21	22	23	24	25	26	27	28	29	30																				
	11	12	13	14	15	16	17	18	19	20																				
	1	2	3	4	5	6	7	8		10																				
	61	62	63	64																										
	51	52	53	54	55	56	57	58	59	60																				
	41	42	43	44	45	46	47	48	49	50																				
2	31	32	33	34	35	36	37	38	39	40																				
	21	22	23	24	25	26	27	28	29	30																				
	11	12	13	14	15	16	17	18	19	20																				
	1	2	3	4	5	6	7	8		10																				
	61	62	63	64																										
	51	52	53	54	55	56	57	58	59	60																				
	41	42	43	44	45	46	47	48	49	50																				
1	31	32	33	34	35	36	37	38	39	40																				
	21	22	23	24	25	26	27	28	29	30																				
	11	12	13	14	15	16	17	18	19	20																				
	1	2	3	4	5	6	7	8	9	10																				

Conditional Failure

Table A-13. Subject Cross Reference for Bunker Test.

Subject Number	Subject ID
1	1012
2	1013
3	1015
4	1016
5	1022
6	1023
7	1032
8	1033
9	1035
10	1036
11	1042
12	1043
13	1046
14	1052
15	1053
16	1055
17	1056
18	1062
19	1063
20	1065
21	1072
22	1073
23	1075
24	1076
25	1082
26	1092
27	1093
28	1095
29	1096
30	1102
31	1105
32	1106
33	1112
34	1113
35	1116
36	1122
37	1123
38	1125
39	1126
40	1132
41	1133
42	1135
43	1136
44	1142
45	1143
46	1152
47	1153
48	1155
49	1156
50	1163
51	1165
52	1166
53	1172
54	1173
55	1182
56	1183
57	1185
58	1186
59	1192
60	1195
61	1196
62	1203
63	1205
64	1206